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by

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1. Introduction

In a recent paper Clark (1956) describes an aircraft thermometer which on theoretical considerations has a sensibly constant recovery factor. Confirmation of the theory was obtained by wind tunnel testing, but as there is often a considerable difference between tunnel and flight conditions it was decided to test the thermometer in free flight. The details of these tests and the results obtained are set out below.

2. Construction and mounting

The thermometer was mounted on a hollow metal rod attached to the port wing tip of Canberra aircraft No. W.J.582 of the Meteorological Research Flight at Farnborough. The rod projects forward a distance of about 3 feet ahead of the leading edge of the wing in order that the thermometer element may be in airflow unaffected by the wing surfaces and tips. Photographs of the mounting are shown in Fig. 1 and 2.

The thermometer was made to the specification and drawings set out by Clark (1956) with one slight alteration. The metal former upon which the resistance element is wound was made of dural instead of thermo-pure aluminium, since the latter was found to be almost impossible to machine to the required standard of accuracy. This change could not in any way affect the aerodynamic performance of the thermometer and laboratory tests failed to show any significant increase in the lag. A close-up of the completed instrument is shown in Fig. 3.

3. Instrumentation

The element was used in conjunction with a standard Meteorological Office Mk. 2(b) balanced bridge indicator mounted in the observer's compartment. The thermometer and bridge were calibrated both before and after the flights in order that any drift or other errors might be detected. The aircraft also carried a flat-plate thermometer mounted under the nose (see Fig. 2) and connected to a balanced bridge indicator in the observer's compartment. The readings of this thermometer were used as a check on those of the conical head.

4. Flight procedure

On each flight readings of conical head, flat plate and I.C.A.N. altimeter were taken simultaneously by the observer every half minute, while at the same time the aircraft navigator read the radar altimeter and airspeed indicator.

The speed runs were carried out on the lines of those done by Durbin (1955) and consisted of five-minute runs on two reciprocal bearings, one at low speed (about 160 kt indicated airspeed at all heights) and the other at as high a speed as possible (420 kt I.A.S. at 10,000 ft decreasing to 230 kt I.A.S.

/at

at 40,000 ft). Ten sets of runs were made altogether at heights of 10,000 ft, 20,000 ft and thereafter at 5,000 ft intervals to 40,000 ft. In addition a set of runs was made at 10,000 ft indicated height in which the speed of each run was increased by 30 kt to cover the speed range from 160 kt to 420 kt indicated airspeed. These latter runs were all done on one flight.

5. Data

Corrections for instrumental error were applied to all the instruments except the radar altimeter, which was only used as a check on the I.C.A.N. altimeter readings. The airspeed indicator and altimeter readings were corrected for position and compressibility errors.

The values of the recovery factor (λ) were computed from the equation given in the Appendix, which is very similar to that used by Durbin (1955). The values of the temperature increment δT due to the difference in the pressure heights of the fast and slow runs were obtained from representative radio sonde ascents for the day and time of the flight. The differences so obtained did not affect the values of the recovery factor by more than 2 per cent on any individual value. The values of the specific heat at constant pressure used were those given by Clark (1951). Finally the recovery factors were recomputed after an attempt had been made to correct the thermometer readings for radiation errors on the basis of Clark's figures ((1956) Table 5), assuming the emissivity to be 0.15.

6. Results

The results of the flights for both conical head and the flat-plate thermometer are set out in Table 1 below as mean values for each level:-

Table 1

Height (1,000 ft)	No. of obs.	Flat plate		Conical head			
				No radiation correction		Radiation correction applied	
		λ	σ	λ	σ	λ	σ
10	8	.76	.022	.88	.030	.88	.026
20	9	.78	.026	.86	.027	.87	.015
25	7	.81	.028	.87	.017	.88	.025
30	9	.84	.017	.87	.024	.87	.025
35	8	.88	.063	.90	.063	.91	.065
40	10	.85	.057	.87	.050	.89	.047
Mean		.822	.035	.88	.035	.88	.034
Mean all values		.823	.058	.88	.041	.88	.026

In this table λ = recovery factor, σ = standard deviation.

The results of the second flight series are shown in Fig. 4 as a graph of indicated temperature against (equivalent airspeed)^2/ pressure, and the values of the recovery factors computed for this flight are

Conical head $\lambda = 0.87$
Flat plate $\lambda = 0.75$

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7. Discussion

An examination of the values of the recovery factor λ obtained shows that for the conical head they remain sensibly constant up to 30,000 ft but that there is an increase above this height especially when radiation corrections were applied. Above 30,000 ft the standard deviation was more than doubled. This last result is also apparent in the standard deviations for the flat plate and is noted by Durbin (1955). The flat plate shows a fairly steady increase in recovery factor up to 35,000 ft and then a decrease. Pairs of values of λ for each thermometer were next tested for significant difference using Student's t-test (Fisher (1946)) as follows. The mean value of λ for 10,000 ft for the conical head was tested with that for 20,000 ft and the probability that the two arose from the same population determined and the determination was then repeated for all possible combinations. The probabilities obtained were not less than 0.15 for any pair. Thus it is reasonable to conclude that the recovery factor of the conical head can be regarded as sensibly constant. Similar tests were applied to the flat-plate thermometer and the probability varied from 0.6 to 0.01, being largest where the two levels were adjacent and least where they were furthest apart, as might be expected from the values obtained. In this case the assumption of a constant recovery factor does not seem justified. Graphs of recovery factor against height for the two thermometers are shown in Fig. 5.

As a further comparison the mean values for each level were correlated with height and regression lines obtained. The values are set out in Table 2. The correlation coefficients were tested for significant difference

Table 2

	Conical head		Flat plate
	No radiation cofrection	Radiation correction applied	
Correlation coefficient (r)	0.118	0.504	0.924
Probability of significant difference from zero	0.82	0.25	0.01
Regression line (h = ht. x 10^{-4})	0.873 + 0.0014h	0.865 + 0.006h	0.718 + 0.039h

from zero. In tests of this type a low probability is associated with a highly significant difference and vice versa. The low correlation coefficient for the conical head, especially when no correction for radiation errors is made, points to the non-dependence of the recovery factor upon height, and this is reflected in the slope of the regression line. Furthermore, it suggests that the radiation correction applied is too large and that the true correction is of such small proportions that for practical purposes it can be ignored.

The increased variances at above 35,000 ft require some explanation. They can arise from four causes:

(i) change of airflow over the entire aircraft causing fluctuations in λ

(ii) the generation of shock waves on the thermometer elements

(iii) changes of airflow over the thermometers due to a turbulent boundary layer causing fluctuations in the values of λ

/(iv)

(iv) instrumental errors in the airspeed indicator and altimeter at high altitudes and high Mach numbers.

The first of these can be ruled out on the grounds that it would seriously impair the performance of the aircraft and lead to stalling. The stalling speed of a Canberra is about 110 kt indicated airspeed at all heights or about 50 kt less than the speed of the slow runs.

The formation of shock waves would affect the flow over the thermometers if such a wave occurred near or in contact with them. The faster of the two runs was carried out at approximately Mach number 0.81 and the occurrence of shock waves is therefore not unlikely. The conical head thermometer has a shock wave attached to the apex of the cone at speeds approaching that of sound other than about $M = 0.95$ to $M = 1.046$ in which range it is slightly ahead of the apex (Taylor and McColl (1933)). There is also another at the point where the slant of the cone curves round to fit into its holder. Neither of these would affect the element. However, any irregularities in the join between the metal element cover and the paxolin body of the cone would generate further shock waves which would be in contact with the thermometer element itself and would therefore affect its readings. The flat plate is somewhat different in that there will certainly be a shock wave at the leading edge of the plate and also at each of the leading edges of the radiation shield. The line of these last two might well intersect the thermometer element and cause additional interference. Failure of these to affect the behaviour of the thermometer below 35,000 ft can be ascribed to the fact that only at the highest two levels was Mach number 0.81 exceeded and for $M < 0.80$ the intensity of the shocks is likely to be small. An examination of the individual values of λ for the two levels concerned shows that there are three anomalous values at 35,000 ft and two at 40,000 ft, all of which are considerably larger than the rest. This applies to both thermometers and the anomalous values all occurred on the same flights. The correlation between the anomalous values and the Mach number of the corresponding high-speed runs is -0.67 for the conical head and -0.66 for the flat plate. These are significant at the 20 per cent level. The number of observations in the sample is only five, and much stress cannot therefore be laid upon this result. It does, however, indicate a possible source of variation, although the fact that the anomalous values occur always on the same flights for both thermometers points more strongly to some other cause extraneous to the thermometers themselves.

The third possible source of the large scatter, namely, change of character of the airflow over the thermometers, is not thought likely to provide anomalies of the sort found. For if following Clark (1952) a change of boundary layer flow from laminar to turbulent at Reynolds numbers 0.5×10^5 (unit of length = 1 cm throughout) is postulated, then theoretical considerations require that the change of flow is in fact from a turbulent to a laminar boundary layer in order to be consistent with the values of recovery factor obtained for the lower levels. At the highest two levels the speed runs are done at Reynolds numbers less than 0.5×10^5, and the anomalous values must therefore be due to laminar boundary flow for which the recovery factor is less than that for turbulent flow. If we assume that the change, contrary to considerations of Reynolds number, does take place from laminar to turbulent boundary and substitute the appropriate values in the expression given by Clark (1951) for the recovery factor, only about half the difference between the two sets of values can be explained. Furthermore the simultaneous occurrence of the anomalies with both thermometers would imply that the boundary layer changes occur together over each thermometer and in view of their different geometrical shapes this seems most unlikely to occur.

Finally the fact that the fluctuations occur at the same time for each thermometer suggests that their cause is unconnected with the thermometers themselves or the airflow over them. A further pointer in favour of this is the two different positions of mounting, one at the wing tip and the other at the nose. An extraneous source of error can arise from only two instruments, the

/altimeter

altimeter and the airspeed indicator. It seems likely therefore that irregularities in the behaviour of either or both of these instruments at high altitude or Mach number are the sources of the large variances.

The single flight at 10,000 ft with increasing speeds for each run provides a slight measure of confirmation of this last suggestion. The top speed reached on this run was M = 0.76 so that the conditions of the runs above 30,000 ft do not obtain and in addition the range of Reynolds numbers covered (0.5×10^5 to 1.27×10^5) precludes extrapolation to the higher levels at which the highest Reynolds number was Re = $.67 \times 10^5$ for the fast runs at 35,000 ft, all other runs being at Re $< 0.5 \times 10^5$. However, the two graphs do indicate a recovery factor for each thermometer which shows little evidence of change with speed and the values obtained (0.87 for the conical head and 0.75 for the flat plate) agree well with the corresponding values obtained by the previous method.

8. Conclusions

It would appear that the conical head thermometer does have a sensibly constant recovery factor within the limitations of speed and height ranges covered by the above flights. The increased scatter at high altitude of the values of the recovery factor when speeds in excess of M = 0.80 are reached stresses the need for a very smooth surface of the instrument especially at the joins of the outer thermometer element and the cone itself, since it is at these points that irregularities giving rise to shock waves can affect the recovery factor. Photographs taken in a wind tunnel at appropriate Mach numbers and corresponding Reynolds number should reveal such effects. The introduction of a radiation correction makes only about a one per cent difference in the results and from a practical point of view seems scarcely worth while at subsonic speeds.

The flat-plate thermometer shows generally an increasing value of recovery factor with height, but little variation with speed at least up to Mach number 0.80 and similar remarks apply to the scatter of the values at high level. The increase in recovery factor is the opposite of that obtained by Shellard (1949) who found a decrease with altitude. This is probably due to the differing angles of attack of the thermometers and also to the angles of attack of the aircraft themselves at high level. It is not clear, however, that the scatter is due to the thermometers. As pointed out in the text it could well be caused by errors in the other instruments involved, namely the airspeed indicator or the altimeter.

The scatter imposes limits upon the accuracy of the measurement of the true air temperature. Taking σ as 0.03 for heights up to 30,000 ft the error in the true air temperature is less than 1°C at true airspeeds less than 500 kt but above this height taking σ = 0.06 the error is only less than 1°C up to 300 kt T.A.S. and is 1-2°C between 300 and 500 kt. The conclusion already reached that the error is not due to the thermometers implies that the development of the latter has reached the limit of its useful accuracy when used with present equipment for measuring altitude and airspeed. A similar conclusion was reached by Durbin (2).

9. Acknowledgements

In writing this report I very gratefully acknowledge the work done by the Meteorological Research Flight who arranged for the mounting of the thermometer and did all the flying involved. I have also pleasure in acknowledging the skill of Mr. B.T. Quilter who made and calibrated the thermometer.

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Appendix

Determination of the recovery factor

The recovery factor is given by

$$T = T_i \Big/ \left(1 + \frac{\gamma-1}{2} \lambda M^2\right) \qquad (1)$$

in which T is the true air temperature, T_i = indicated temperature, λ = recovery factor $(0 < \lambda \leq 1)$, γ = the ratio of the specific heats of air, M = Mach number.

Using suffix 'L' to denote values relating to the low speed run and suffix 'H' for the high speed run and assuming both runs are done at the same height

$$\frac{T_L}{1 + \frac{\gamma-1}{2}\lambda M_L^2} = \frac{T_H}{1 + \frac{\gamma-1}{2}\lambda M_H^2} \qquad (2)$$

In practice, due to errors in the airspeed indicator, it is not feasible to do both runs at the same height. Suppose then that the temperature at the height of the slow run is T and that at the height of the fast run $T + \delta T$ then

$$T = \frac{T_L}{1 + \frac{\gamma-1}{2}\lambda M_L^2} \qquad \text{and} \qquad T + \delta T = \frac{T_H}{1 + \frac{\gamma-1}{2}\lambda M_H^2}$$

whence

$$\frac{T_L}{1 + \frac{\gamma-1}{2}\lambda M_L^2} + \delta T = \frac{T_H}{1 + \frac{\gamma-1}{2}\lambda M_H^2}$$

from which

$$T_H - T_L - \delta T = \lambda \frac{\gamma-1}{2}\left\{T_L M_H^2 - T_H M_L^2\right\} - \lambda \frac{\gamma-1}{2}\delta T\left(M_L^2 + M_H^2\right) - \left\{\lambda\left(\frac{\gamma-1}{2}\right)\right\}^2 M_L^2 M_H^2 \delta T \qquad (3)$$

Now $0 < \lambda \leq 1$ and δT did not amount to more than $\frac{1}{2}$°C. and $M_L^2 + M_H^2$ was always < 1. The ratio of the first and second terms on the R.H.S. is therefore not greater than 1/180 and of the first and third terms not greater than 1/1,000. Thus by ignoring the last two terms on the R.H.S. the error in the determination is certainly not greater than one per cent.

Equation (3) then becomes

$$T_H - T_L - \delta T = \lambda \frac{\gamma-1}{2}\left(T_L M_H^2 - T_H M_L^2\right) \qquad (4)$$

Let suffix zero refer to standard I.C.A.N. values of the variables at M.S.L. Let a be the speed of sound, p be the pressure at the levels concerned and v the equivalent airspeed then with a little manipulation

$$M^2 = k v^2/p \qquad \left(k = p_0/a_0^2\right) \qquad (5)$$

/Substituting

Substituting for M^2 in (4) and solving for λ

$$\lambda = \frac{2(T_H - T_L - \delta T)}{(\gamma-1)k\left\{\frac{T_L v_H^2}{h_H} - \frac{T_H v_L^2}{h_L}\right\}} \qquad (6)$$

This equation, which is substantially the same as that given by Durbin (1955), was used for the determination of the recovery factor.

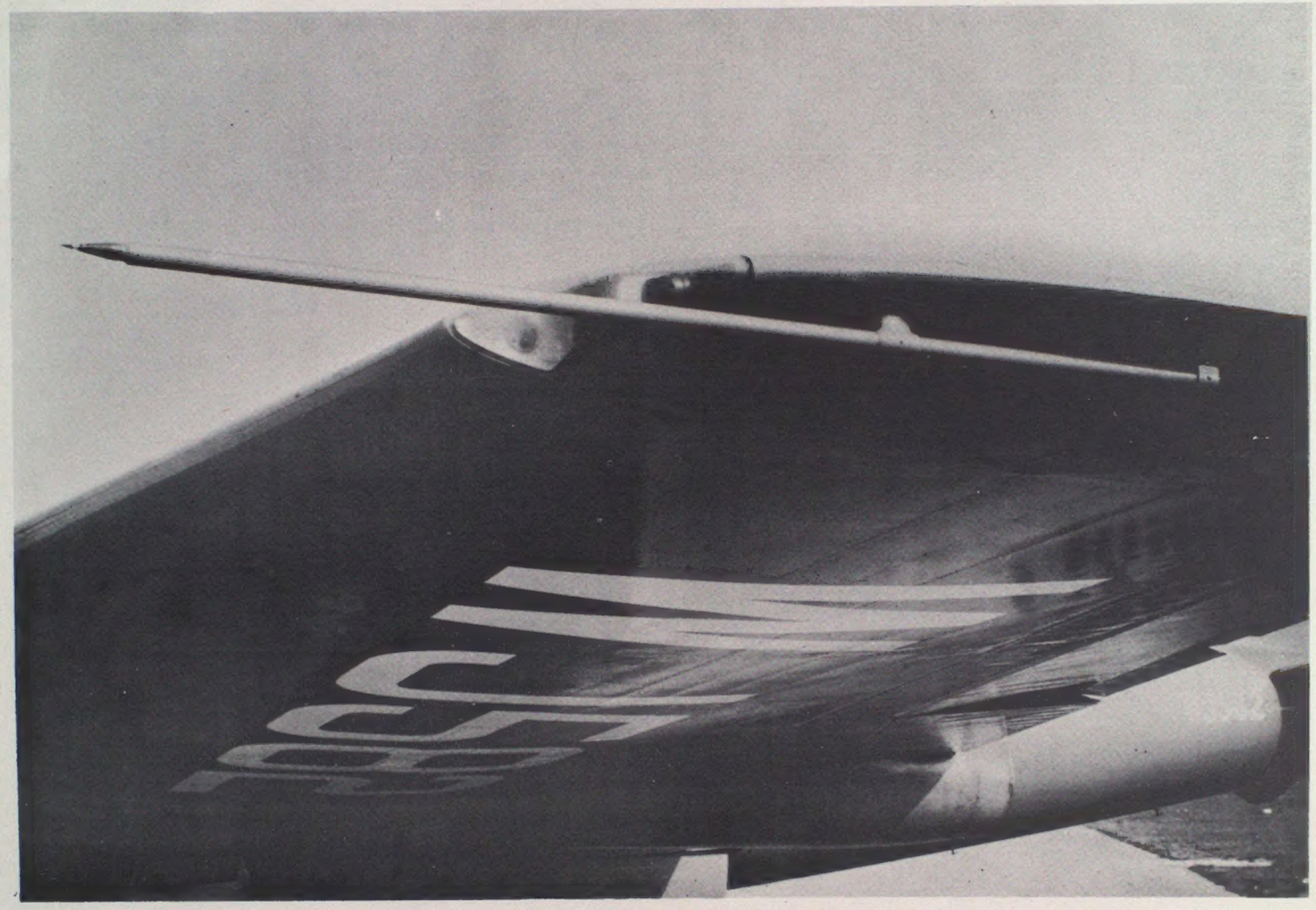

FIG. 1

CLOSE-UP OF THERMOMETER MOUNTED ON WING-TIP OF CANBERRA AIRCRAFT

FIG. 2

CANBERRA WJ582

SHOWING (A) CONICAL HEAD THERMOMETER & (B) FLAT PLATE THERMOMETER

FIG. 3

CONICAL HEAD THERMOMETER

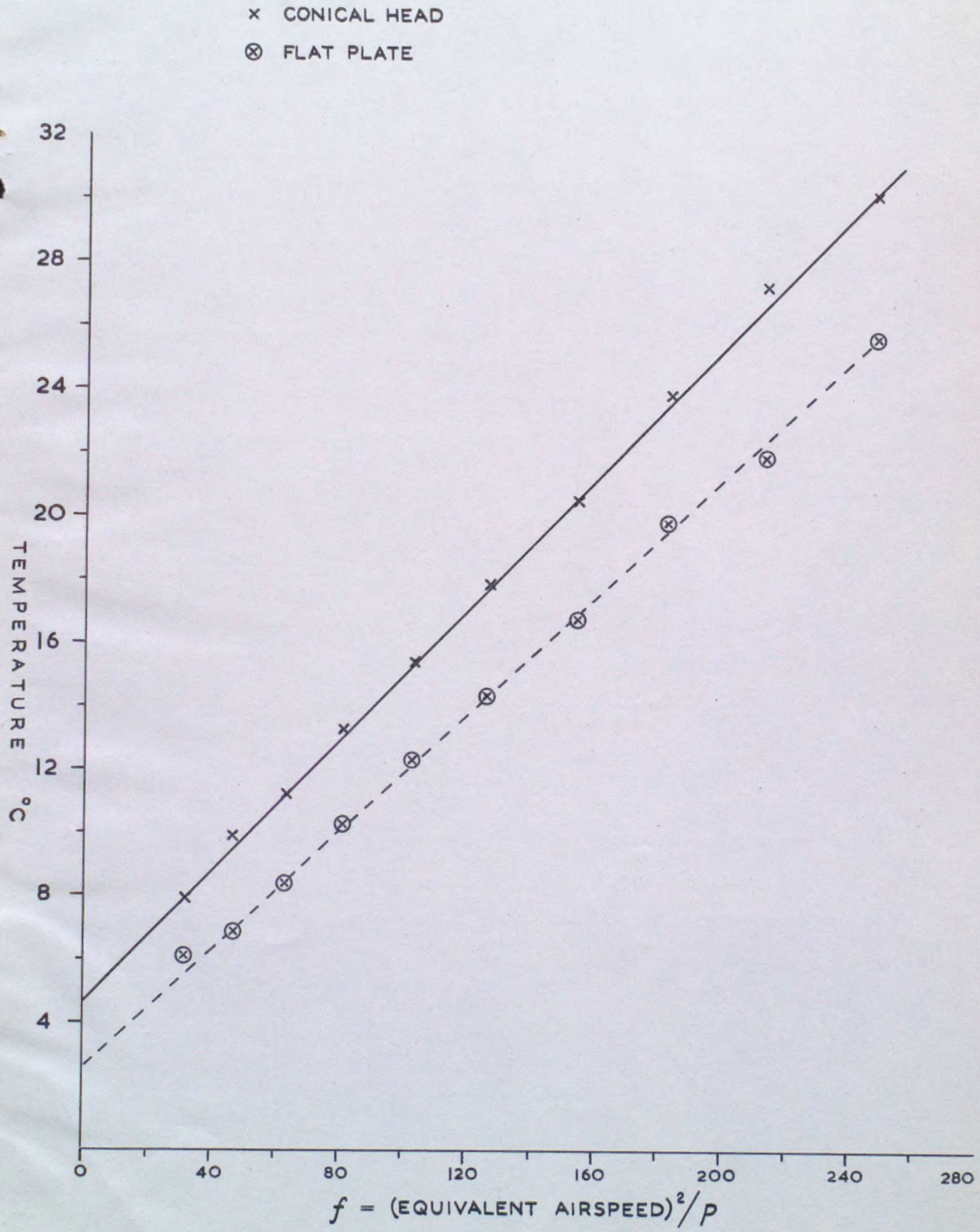
× CONICAL HEAD
⊗ FLAT PLATE
32
28
24
20
16
12
8
4
TEMPERATURE °C
0
40
80
120
160
200
240
280
f = (EQUIVALENT AIRSPEED)²/p

FIG. 4

VARIATION OF RECOVERY FACTOR WITH HEIGHT

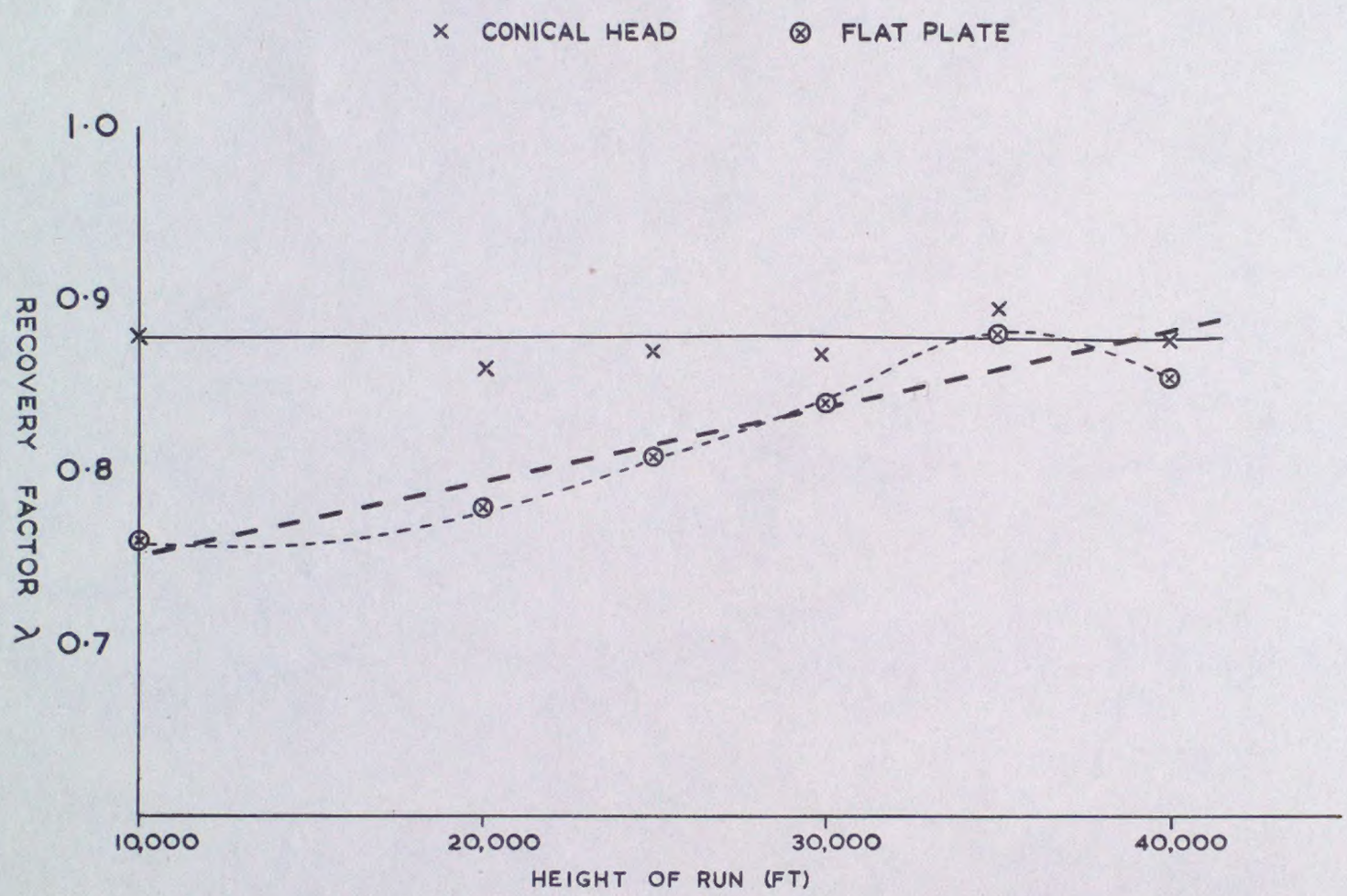

FIG.5